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Monolithic Microwave Integrated Circuit Technology for Advanced Space Communication

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MONOLITHIC MICROWAVE INTEGRATED CIRCUIT TECHNOLOGY

FOR ADVANCED SPACE COMMUNICATION

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SUMMARY

Future Space Communications subsystems will utilize GaAs Monolithic Microwave Integrated Circuits (MMIC's) to reduce volume, weight, and cost and to enhance system reliability. Recent advances in GaAs MMIC technology have led to high-performance devices which show promise for insertion into these next generation systems. The status and development of a number of these devices operating from Ku through Ka band will be discussed along with anticipated potential applications.

INTRODUCTION

GaAs monolithic microwave integrated circuit (MMIC) technology has progressed to the point that their integration into space communication systems is now feasible on a large scale. As a result of advances in the quality of semiconductor materials, improvements in microwave design techniques, development of improved fabrication technology, and batch processing techniques, GaAs MMIC's can now offer the system designers high performance, small size, high reliability, reproducibility, low cost, and high-volume production.

Improvements in microwave materials and the methods for their production have permitted both improved performance and lower cost. Semi-insulating GaAs has decreased significantly in cost while having better electrical characteristics compared to earlier substrates. In addition, active layer formation by such methods as ion implantation, molecular beam epitaxy (MBE), metal organic chemical vapor deposition (MOCVD), and vapor phase epitaxy (VPE) permits the preparation not only of the basic MESFET structure, but also heterojunction structures such as High Electron Mobility Transistors (HEMT's) which exhibit improved noise figure performance and appear to promise improved millimeter wave performance in power applications.

Fabrication techniques have improved to a point where via holes, air bridges, thin film resistors, metal-insulator-metal capacitors, and spiral inductors are now routinely made. In addition, optical lithography at a resolution of 0.5 μm is now possible on large wafer lots offering a reduced cost in comparison with E-beam direct write lithography.

Microwave design capabilities below 20 GHz have progressed rapidly. Computer aided design programs such as Touchstone and Super Compact can both be used for circuit simulation and optimization. Above 20 GHz the programs can be used but more care must be taken with the models. Many MMIC designers have also developed a library of models to supplement the capabilities of the two

programs. The other break through which has quickened the design turn around time was the development of the on-wafer probing station by Cascade Microtech.

NASA Lewis Research Center recognized the advantages of MMIC's in space communications and initiated a program in MMIC development approximately 6 years ago. The major thrust of our effort since then has been the development of MMIC's which would push the state of the art in both circuit complexity and performance while providing technologies needed for NASA's communication needs. Specifically, the development of 30-GHz receivers and 20-GHz transmitters for use on an ACTS-like satellite with scanning phased array antennas, Ku-band high-efficiency amplifiers for space station, 32.5-GHz power amplifiers and phase shifters for the Mars Rover mission, and 60-GHz amplifiers and phase shifters for interorbiter communications was undertaken.

NASA has constantly been incorporating new technologies into the programs as they developed. The earlier programs used GaAs MESFET technologies which were still state of the art in 1981-1982 when the programs were initiated. HEMT technology was incorporated into the programs when it became apparent HEMT's would offer greater performance for certain applications such as low-noise amplifiers.

In addition to these basic MMIC developments, NASA Lewis has initiated contracts to develop the necessary devices and circuitry for optical control of an MMIC. This development should provide a further stimulus to use MMIC's in large antenna arrays by simplifying the control line and RF feed distribution networks. The accomplishment of this goal promises to reduce the weight and size of communication systems.

The goals and status of the above stated developments are given in the next section. Lastly, areas which need further development are discussed.

Ku-BAND HIGH-EFFICIENCY POWER AMPLIFIER

In anticipation of Space Station needs, NASA Lewis has awarded parallel contracts to Hughes Aircraft Corp. (HAC) and Texas Instruments (TI) for the development of GaAs MMIC high-efficiency power amplifiers. Three different MMIC chips are being developed under each contract: A 4.0-W high-power amplifier (HPA), a 1.0-W medium-power amplifier (MPA), and a 1.0-W variable-power amplifier (VPA). The design goals for the contracts are listed in table I.

The specification on the efficiency is the most stringent of the design goals. To meet that goal, HAC has chosen a class B push-pull amplifier design which has a theoretical drain efficiency of 78.5 percent and a corresponding power added efficiency of 76 percent for the specified gain of 15 dB. A class A amplifier with a theoretical drain efficiency of 50 percent would have a corresponding power added efficiency of 48.4 percent. Since practical devices have a nonzero resistance across the channel, the actual efficiencies obtainable will be less than those stated above. Therefore, the class B amplifier design is a logical choice for obtaining the 40 percent efficiency specified. In addition, class B push-pull operation suppresses even order harmonics.

The class B push-pull amplifier designed by Hughes is one of the most complicated MMIC's attempted so far. The HPA chip layout is approximately 4.1 by 2.6 mm and contains 19 via holes, 50 thin-film capacitors, 14 thin film resistors, more than 100 air bridges, and three stages of 0.5 μm FETS with a combined width greater than 12 mm. The VPA will employ dual-gate FETS for gain control.

Texas Instruments has selected a class AB amplifier as a baseline approach. Texas Instruments is also investigating high-efficiency devices as alternatives to GaAs MESFETS. As part of the contract, TI is to deliver a nominal number of GaAlAs/GaAs heterojunction HEMT and GaAlAs/GaAs heterojunction MISFET HPA MMIC's. These modules should have a higher efficiency than the GaAs MMIC's of similar circuit design. Each amplifier will use three stages of 0.5-μm gate-length FETs. Recently, TI demonstrated a 1200 μm wide device grown by molecular beam epitaxy with an n+ contact layer and a 2.5×10^{17} cm^{-3} doped active layer which exhibited a power density of 0.5 W/mm and an efficiency of 39 percent.

Both contractors are to passivate all the MMIC's and deliver them in hermetically sealed packages. The package design should address the issues of MMIC protection, compatibility with RF test systems, thermal dissipation, and compatibility with the system requirements. A well designed package should allow the timely incorporation of the MMIC's into a system. In general though, the issue of MMIC packaging is not a trivial problem and further comments on this issue are addressed in the conclusion section of this paper.

30 GHz MMIC RECEIVER TECHNOLOGY

NASA Lewis has two contracts for the development of 30-GHz GaAs MMIC receivers. The development of the receiver was separated into four separate module developments: a phase shifter, low noise amplifier (LNA), mixer, and a gain control amplifier (GCA). Technologies which would permit the integration of the submodules into a complete MMIC receiver were to be used. Although both contractors were to design a receiver to meet the specifications in table II, each used a different approach. Hughes performed the phase shifting at the LO frequency and the gain control at the IF frequency. Honeywell performed the phase shifting and gain control at RF. The block diagram for each of the circuits is given in figure 1.

The contract with HAC has been completed. The performance of the individual submodules is given in table III. The HAC LNA used two stages of 0.25- by 150-μm T-shaped gate FET's fabricated by direct E beam write lithography and ion implantation into a VPE buffer layer. Although the LNA did not meet the specifications, it did obtain state-of-the-art performance for that time (fig. 2). Yield limitations were primarily caused by MOM capacitor defects. Hughes worked on this problem and was finally able to fabricate MOM capacitors with a capacitance per unit area variation of 2 percent across a wafer and 5 percent from wafer to wafer. The GCA used a 0.5-μm dual-gate FET to achieve the required gain control. Inadequate matching of the schottky diodes to the circuit caused the mixer to require 17 dBm of LO power to achieve the reported conversion loss.

Hughes used an analog phase shifter design shown in figure 3. Reverse biased varactor diodes, which act as variable capacitors, are in series with an inductor. By changing the bias on the diodes, the diode capacitance and therefore the reactance of the LC circuit is changed. Therefore, the phase of the reflected signal into ports 2 and 4 of the Lange coupler is changed. A phase change between 90° and -90° is possible with the proper capacitance variation. Higher frequency operation of phase shifters using this design is limited by the series resistance and the capacitance variation obtainable by the varactor diodes. Therefore, cascading two or more phase shifters to obtain 180° of phase shift with low loss is necessary at Ka-band and higher frequencies.

The phase shifter, mixer, and GCA were integrated by HAC into one MMIC (fig. 4). This was feasible since all the devices used optical lithography and ion implantation for active area definition. Unfortunately, the resulting MMIC did not work due to gate misalignments and poor device isolation caused by the multiple implants required to define all the different devices. The few chips which had working components showed that integration of diodes and FET's on the same chip is possible. The gate misalignment could have been solved by better alignment marks and the device isolation could be accomplished by a proton bombardment step. The LO signal was not applied to the phase shifter in the integrated MMIC since the diodes in the phase shifter could not handle the LO power required by the mixer. The LNA was not integrated onto the circuit because of its low yield and the high cost of E-beam lithography. Due to time and money constraints, HAC did not correct these problems or design the circuitry necessary for digital control of the phase shifter and gain control amplifier (ref. 1).

Honeywell has demonstrated and delivered to NASA the LNA, phase shifter, and GCA. The measured results achieved by Honeywell are given in table III. Honeywell's analysis determined the LNA must provide 32 dB of gain with a 4.8-dB noise figure, which translates to roughly 6-dB gain and 4-dB noise figure for each of the five stages, to achieve the required receiver performance. The LNA was fabricated using ion implantation and hybrid E-beam/optical contact lithography to define 0.25- by 100-μm gate FETs. Recent testing on a two-stage LNA yielded 7-dB gain with 6.2-dB noise figure at normal bias. On chip matching modifications are required to shift the operating frequency to the NASA 27.5- to 30.0-GHz band. The GCA, like the LNA, utilizes ion implanted 0.25- by 100-μm gate FETs; however, dual-gate technology is used to obtain gain control. Two stages of amplification are required to achieve a maximum 12-dB gain with 13-dB dynamic range. A phase envelope of ±10° at band center was obtained over the dynamic range. Chip size is 1.8 by 0.5 by 0.15 mm^3.

The Honeywell phase shifter is comprised of three switched line bits, 45, 90, and 180°, and a loaded line section. The switched line bits vary the phase of the signal by adding or subtracting incremental lengths of transmission line (fig. 5). One- by 400-μm gate FET's fabricated by ion implantation using power FET processing techniques are used in the Single Pole-Double Throw (SPDT) switches. The measured insertion loss at band center is less than 2 dB per bit. The variation in the insertion loss when the phase shifter is stepped over the 16-phase states is ±2 dB. Chip size is 2.5 by 5.5 by 0.15 mm^3.

The RF/IF downconverter uses a balanced mixer with an IF of 5.5 to 8.0 GHz and employs ion implanted schottky barrier diodes. The mixers are fabricated using an advanced CENSOR direct-step on-wafer lithography system. The diode

processing is compatible with the FET technology to facilitate monolithic integration with the other functions. Measured RF performance of the 3.1- by 2.2- by 0.15-mm^3 chip indicated a conversion loss of 8 dB at +10 dBm LO drive. The high conversion loss, which exceeded the desired goal by several dB, is attributed to mismatch between the diodes and the hybrid LO/RF combining circuit. A redesign has been initiated. A three-stage LO-buffer amplifier with a measured 16-dB gain at 22 GHz has also been developed as part of the submodule.

To demonstrate the potential of a monolithic receiver, Honeywell cascaded the LNA, phase shifter, and GCA submodules. The interconnected receiver demonstrated the compatibility of the submodules and the expected overall performance of the MMIC. All the tested interconnected receivers yielded comparable results. Gain and phase data are shown in figure 6. At present, additional runs with design modifications are being initiated to improve performance of the LNA and phase shifter submodules. Additionally, a monolithic version of an LNA/Phase shifter chip is being processed (ref. 2).

20 GHz TRANSMITTER TECHNOLOGY

NASA Lewis has three contracts to develop MMIC's for a 20-GHz transmitter. The first contract is with Rockwell International (RI) for the development of a variable phase shifter, constant gain amplifier, and the digital control circuitry for the phase shifter integrated into a single circuit. The other two contracts are both with TI for the development of a variable-power amplifier and a high-power amplifier. The goals for these three contracts are given in table IV.

The MMIC developed by RI is shown in figure 7. It includes a five-bit variable-phase shifter with nominal settings of 11.25, 22.50, 45, 90, and 180° followed by a buffer amplifier to compensate for the loss in the phase shifters. All five bits of the phase shifter are the switched line type described above. The final stage is a constant gain amplifier. With the successful integration of the digital control circuitry, the MMIC obtained the highest level of integration for a 20-GHz MMIC reported at the time (ref. 3).

The VPA consisted of a four-stage GaAs FET amplifier with a D/A converter (fig. 8) to convert a four-bit control signal into 16 discreet voltage levels from -3 to 3 V. The output power of the amplifier was controlled through the use of dual-gate FET's with the second gate of the FET biased by the output voltage of the D/A converter. This approach permits a large dynamic range of gain control, low phase variation over the dynamic range, and FET input/output impedances which are nearly constant. TI used 0.4- to 0.5-μm gates defined on a VPE grown active layer. The four stages had gate widths of 240, 240, 480, and 1200 μm for a total gate periphery of 2.16 mm. TI has measured 500 mW of output power with 21 dB of gain and 14.9 percent power added efficiency at 18 GHz. The measured linear gain was 23 dB at 250-mW output power. 30 dB of dynamic range was measured (ref. 4).

NASA Lewis has performed quick measurements of 100 of the VPA's which TI packaged in a NASA supplied package. An average peak gain of 22.0 dB over a 1-GHz bandwidth centered at 18 GHz was measured. The results in the upper portion of the 17.7- to 20-GHz band are slightly degraded. The D/A controlled dual-gate FET's provided only marginal gain control; the apparent lack of gain

control is being investigated. The chip-to-chip repeatability across a wafer was good but wafer-to-wafer variations were large (ref. 5).

Two approaches were tried by TI in the development of the power amplifier design. The first used a four to one traveling wave power combiner and four 0.7-W amplifiers. Although TI successfully demonstrated a power combiner with 0.35 dB of insertion loss from 2 to 21 GHz and a distributed amplifier with 0.5-W output power, an average gain of 4.0 dB, and 14 percent power added efficiency from 2 to 21 GHz, this design was not used because of the large size of the resulting MMIC and the low power and gain which was achieved. The second approach used a three-stage power amplifier (fig. 9). The FET's had 0.5-μm gates with a total gate periphery of 9.6 mm. The best measured performance achieved 2.5-W output power, 18-dB gain, and 16 percent power added efficiency at 18 GHz (ref. 6).

NEXT GENERATION MMIC TECHNOLOGIES

The GaAs MESFET has been the driving force behind the MMIC industry in the past. Microwave circuit design and testing and GaAs fabrication have matured during that time. Recently though, the fabrication of advanced devices has become feasible with the development of material growth processes which permit complex device geometries. The permeable-base transistor, heterojunction bipolar transistor, and HEMT's are examples of devices now made possible by the advance of MBE and MOCVD material growth processes.

Of the new devices, the HEMT is the most likely technology to be used in the early 1990's. The outward appearance of a HEMT is identical to that of a MESFET. In addition, the same processing technologies are used to fabricate both HEMT's and MESFET's. This should make the integration of HEMT devices into present MMIC design and fabrication processes readily achievable.

HEMT's have been demonstrated to be superior to GaAs MESFET's for the following applications: low-noise amplifiers; distributed amplifiers, they have a higher gain-bandwidth product; and power amplifiers. InGaAs pseudomorphic HEMT's with 0.25-μm gates have been shown to have useful gain above 94 GHz and a power added efficiency of 28 percent at 60 GHz (ref. 7). Hybrid circuits and MMIC's using HEMT's have given state-of-the-art performances (ref. 8 to 10).

The superior performance of HEMT's is due to the separation of the free electrons from the donor atoms in the gate channel region (fig. 10). The separation occurs due to the diffusion of the electrons from the higher energy doped AlGaAs layer to the energy well created by the GaAs/AlGaAs heterojunction. Since the GaAs layer is undoped, the electrons travel in the absence of electron-donor atom scattering. Therefore, the electron velocity and mobility is higher (ref. 11).

NASA has several contracts for the development of the next generation of space communication MMIC's which utilize heterojunction devices. One of these contracts is the Ku-band high-efficiency power amplifier contract with TI which has already been addressed. Another contract with TI is for the development of Ka-band power amplifiers. As part of the contract, TI is to develop a 32.5-GHz GaAs HEMT based power amplifier which is specified to have 20 dB of gain and

0.1 W of output power at 1-dB compression with 20 percent power added efficiency. In addition, a new contract for the development of 32.5 and 60 GHz variable-phase shifters and power amplifiers using HEMT technology has been awarded.

In addition to HEMT technology, the next generation of MMIC's will probably incorporate optical circuitry. MMIC's require both digital control lines, for phase shifter and gain control, and RF and LO transmission lines. Microwave transmission lines, waveguide, and coax, are heavy and large. The replacement of these lines with optical fibers and integrated photodetectors would greatly reduce the weight and size of the system. The distribution of the digital control signals in a phase array would also be simplified with the use of optical technologies. Under a NASA contract, Honeywell is developing a photodetector and 1:16 demultiplex chip which will operate at 1 G Bit/sec and when integrated with a four-bit phase shifter, the integrated chip will have a total power consumption of 750 mW. Testing of the circuits fabricated to date indicate that the demultiplex chip will meet all the contract goals. The detector has not been tested yet at high data rates.

CONCLUSIONS

NASA's MMIC development efforts and those reported in the literature have shown that "large scale" integration of microwave components is feasible. There is further evidence of this in the Defense Departments MIMIC programs. This program is estimated to be worth $500 million for the demonstration of manufacturability, low cost, testability, and reliability of MMIC's. Although the primary goals of the MIMIC program are to supply MMIC's which are insertable into DoD's programs, the developments made should show direct benefits for space communication circuits.

The results of NASA's programs also show that although it may be possible to fabricate a fully integrated receiver or transmitter, this may not be economically practical at this time. The major problem to this desirable goal is the low yields obtained and therefore the high cost of the MMIC circuits. This may be partly due to the fact the contracts discussed were for the development of state of the art devices requiring nonproduction line types of fabrication processes. As processing developments for the fabrication of gates less than 0.5 μm long are made, the yield of these devices will surely increase. The optimum level of integration will have to be addressed periodically as advances are made which effect fabrication yield.

Finally, there are several issues which need to be addressed before the benefits of MMIC's may be fully realized. The major concern is the passivation and packaging of the MMIC in a hermetically sealed enclosure which does not degrade the MMIC's performance. This is complicated by the fact that microwave transmission lines radiate energy which is easily coupled to neighboring components. The radiated energy can also create resonances within the enclosure. In addition, the bonding of DC and RF feed lines to the MMIC can create parasitic reactances which may degrade the performance of the circuit. Radiation hardness and reliability of HEMT's needs further study before they can be inserted into satellite communication systems. Lastly, millimeter wave circuit component models need to be either created or refined to decrease the amount of design iterations required for MMIC design above 30 GHz.

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11. Berenz, J.: High Electron Mobility Transistors. IEEE MTT-S Newsletter Summer 1984, pp. 43-52.

TABLE I. - Ku-BAND HIGH EFFICIENCY AMPLIFIER CONTRACT GOALS

	MPA	HPA	VPA
Frequency, GHz	13 to 15	13 to 15	13 to 15
Input/output VSWR	1.3:1	1.3:1	1.3:1
Group delay, nsec (over any 500 MHz subband)	0.5	0.5	0.2
RF output power	>1.0 W sat. >0.5 W linear	>4.0 W sat. >2.5 W linear	0 to 1.0 W in 16 levels
Gain	>15 dB	>15 dB	>15 dB at 1.0 W
Added efficiency	>40% sat. >35% linear	>40% sat. >35% linear	>35% at 1.0 W
Gain variation (over the full band)	<1 dB	<1 dB	----------
(over any 500 MHz subband)	<0.5 dB	<0.5 dB	----------

TABLE II. - 30 GHz RECEIVER CONTRACT GOALS

RF band, GHz	27.5 to 30
IF center frequency, GHz	4 to 8
Noise figure (R.T.), dB	<5
RF/IF gain at highest gain control level, dB	30
Dynamic range, dB	>30
Module power consumption at all power levels except off state, mW	250
Phase variation, deg.	180
Phase and gain control	5 bit and 4 bit digital input

TABLE III. - 30 GHz RECEIVER SUBMODULE PERFORMANCES

	Hughes	Honeywell
LNA		
Frequency, GHz	29.6 to 32.2	27.5 to 30
Noise figure, dB	6.7	6.2
Gain, dB	18	7
Yield (D.C.), percent	8 to 27	----------
Notes	Best performance	Tuned for low noise
Phase shifter (PS)		
Type of PS	Analog	4 bit digital
Phase variation, deg.	180	360
Insertion loss (typical), dB	2 to 5	<2 dB/bit
Frequency, GHz	23.5	27.5 to 30
Yield (D.C.), percent	70	----------
Mixer		
Conversion loss, dB	8 to 9	8 to 12
Isolation, dB	3.5 to 6.0	----------
Yield (D.C.), percent	70	----------
Gain control amplifier		
Frequency, GHz	4 to 6.5	27.5 to 30
Maximum gain, dB	12	12
Dynamic range, dB	30	13
Noise figure, dB	5	16.3
Yield (D.C.), percent	52	----------

TABLE IV. - 20 GHz TRANSMITTER CONTRACT GOALS

	Phase shifter	Constant gain amplifier	Variable power amplifier	High power amplifier
Frequency, GHz	17.7 to 20.2	17.7 to 20.2	17.2 to 20.2	19 to 21
RF output power, W	----------	0.2	0 to 0.5 max.	2.5 sat., 1.5 linear
Gain, dB	----------	>16	>20	>15
Added efficiency	----------	>15%	>15% at 0.5 W	>20% at sat.
Phase variation	360°	----------	<5°/bit	----------
Phase/Gain control, bit	5	----------	4	----------

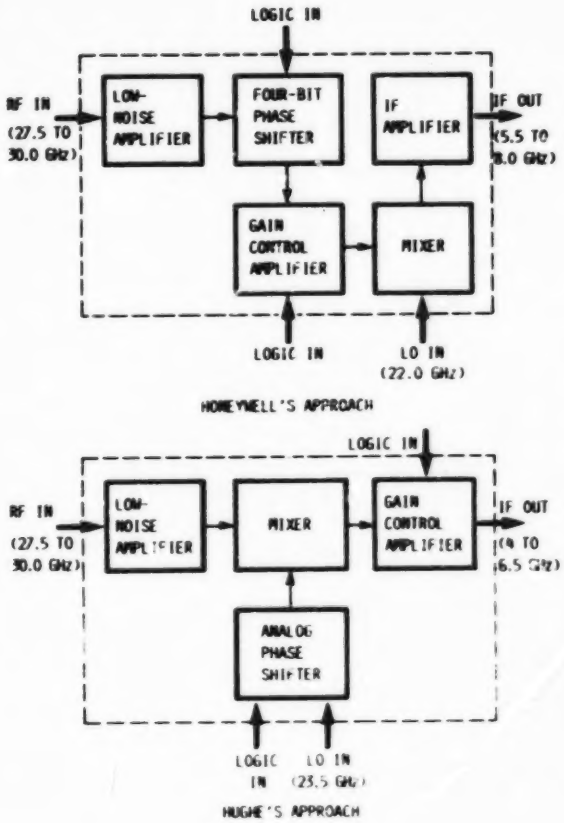

FIGURE 1.

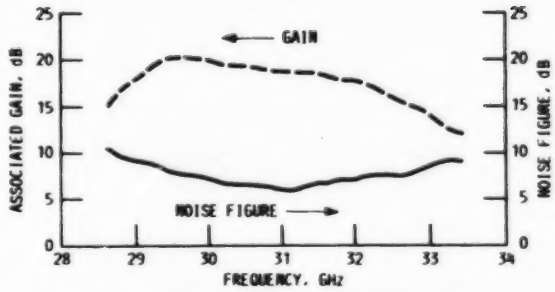

FIGURE 2. - TWO-STAGE QUARTER MICRON LNA PERFORMANCE.

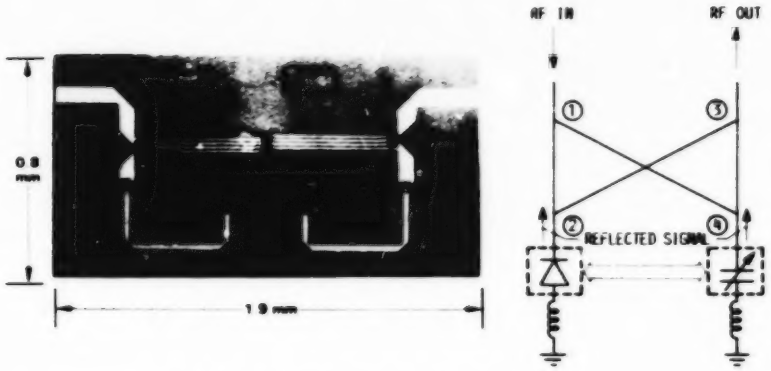

FIGURE 3. - 23.5-GHz ANALOG PHASE SHIFTER.

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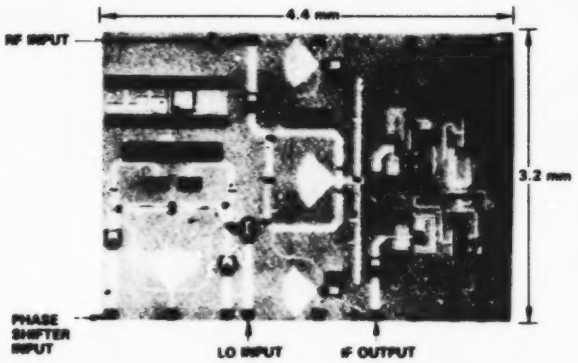
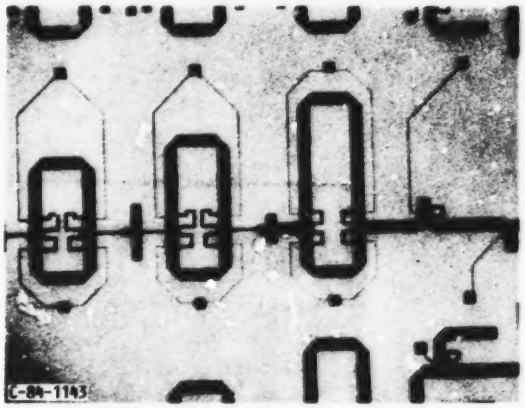
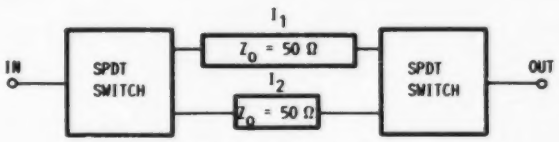


FIGURE 4. - Ka-BAND MONOLITHIC RECEIVER MODULE.



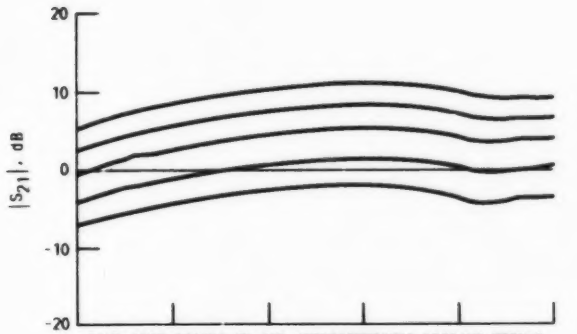
THREE-BIT SWITCHED LINE PHASE SHIFTER



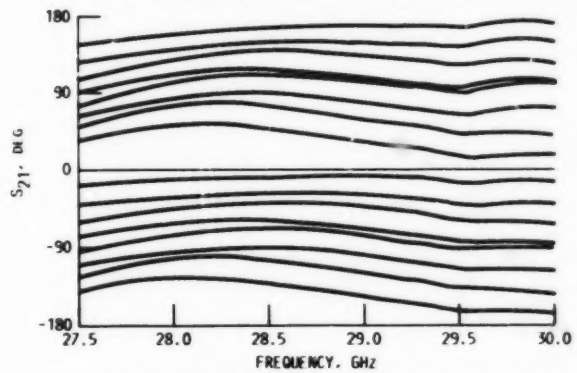
ONE-BIT PHASE SHIFTER

$\theta_1 - \theta_2 = \beta l_1 - \beta l_2 = 180^0$

FIGURE 5. - SWITCHED LINE PHASE SHIFTER.



FIVE GAIN STATES OF THE INTERCONNECTED RECEIVE MODULE AT ZERO PHASE SHIFT. BIAS ON THE SECOND GATE OF EACH STAGE WAS VARIED DISCREETLY FROM 0 TO -0.75 V.



DIFFERENTIAL INSERTION PHASE FOR 16 PHASE STATES OF THE INTERCONNECTED RECEIVE MODULE AT MAXIMUM GAIN.

FIGURE 6. - MEASURED PERFORMANCE OF THE INTERCONNECTED RECEIVER.

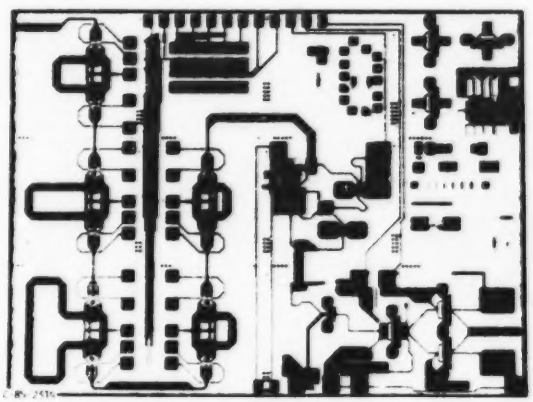


FIGURE 7. - 20-GHz MONOLITHIC TRANSMIT MODULE (6.3 x 4.7 mm).

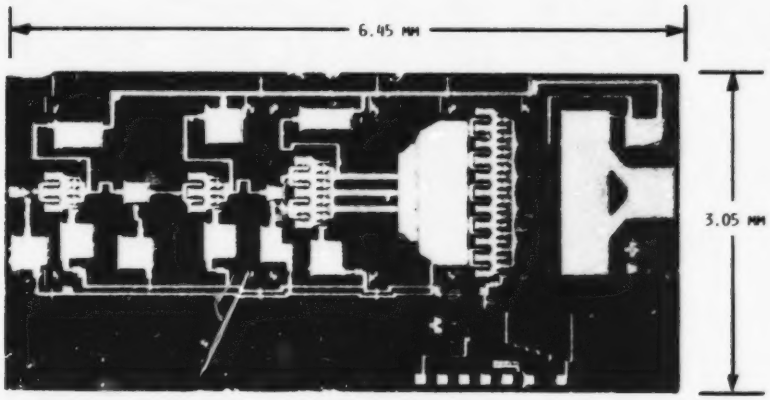


FIGURE 8. - 20-GHz VARIABLE-POWER AMPLIFIER WITH D/A CONVERTER (6.45 x 3.05 MM).

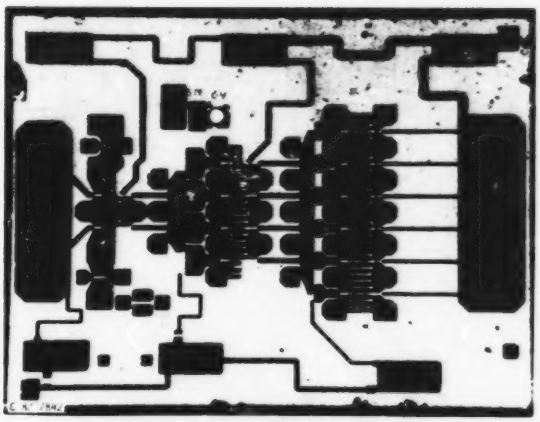


FIGURE 9. - 20-GHz HIGH POWER AMPLIFIER.

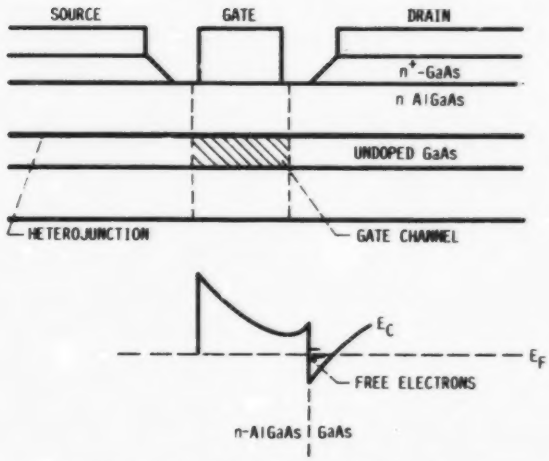


FIGURE 10. - HIGH ELECTRON MOBILITY TRANSISTOR.

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15. Supplementary Notes

16. Abstract

Future Space Communications subsystems will utilize GaAs Monolithic Microwave Integrated Circuits (MMIC's) to reduce volume, weight, and cost and to enhance system reliability. Recent advances in GaAs MMIC technology have led to high-performance devices which show promise for insertion into these next generation systems. The status and development of a number of these devices operating from Ku through Ka band will be discussed along with anticipated potential applications.

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